TEVATRON RUN II PLANS

P. Bagley* for the Tevatron Group
Fermi National Accelerator Laboratory#, P.O. Box 500, Batavia, IL, 60510

Abstract

This is a brief overview of the Tevatron plans for the upcoming Collider Run II [1] with special attention to beam beam problems. Presently we have finished the Fixed Target Run and are in the process of switching over to Collider Mode. The Fixed Target run went well and was a successful first pass at incorporating the new Main Injector into the Fermilab complex of accelerators. Although there will be several shutdowns, we will remain in Collider mode indefinitely (at least until the LHC is running).

1 THE SCHEDULE [2]

Early May 2000 – The Tevatron is scheduled to turn back on.

May 2000 – Most of May will be spent re-commissioning Power Supplies and doing high energy testing. As the culmination of several years of work, the top beam energy of the Tevatron will be raised from 900 GeV to at least 980 GeV and hopefully to 1 TeV.

May to end of July 2000 – The Engineering Run. We will mainly be working only with protons (no pbars) re-commissioning the machine.

First 2 weeks of Aug. 2000 – After at least one 36 X 36 store, we will shutdown and an incomplete CDF detector will be rolled into the beam line. It will be missing its Silicon Vertex Detector and possibly parts of a few other sub-systems.

Mid Aug. 2000 to the end of Oct. 2000 – The Commissioning Run. We will be establishing Colliding Beam conditions and CDF will begin to shake out their upgraded detector.

Nov. 2000 to the end of Feb. 2001 – Shutdown for the D0 experiment to roll into the beam line. Also, CDF will roll out, install their Silicon Vertex Detector and any other needed components, and roll back in.

March 2001 – Run II begins!

2 CHANGES FROM RUN IB

The biggest change from Run I is the increase from 6 to 36 bunches per beam. 36 bunches per beam corresponds to a minimum bunch spacing of 396 nsec.

2.1 Motivation for 36 bunches

The peak luminosity achieved during Run IB was 2.8e31/(cm^2 sec). For 6 X 6 bunch operation, this corresponds to about 4.9 inelastic interactions per bunch crossing. Multiple interactions per crossing makes the event reconstruction and physics analysis more difficult. The number of interactions per crossing (IC) the experiments can tolerate is an involved question and depends on the type of physics analysis being attempted. Generally, CDF would prefer no more than about 3-4 IC, and D0 would prefer no more than about 1-2 IC.

The limit on the number of interactions per crossing combined with the experiments' obvious desire for more luminosity, pushes us to more bunches.

2.2 Changes to the Other Machines

This will be the first Collider run with the Main Injector (MI). The Main Injector has performed well in the Fixed Target Run, but for Collider operations, it will have many more roles to perform.

There have been major upgrades to the Pbar Source (the Debuncher and the Accumulator). Almost every stochastic cooling system has been replaced, the lattice of the Accumulator has been changed, and they will have to deal with much more beam on target. One of the big questions for Run II is just how many pbars will we have available? What will be the pbar stacking rate?

The Recycler is a new machine that is still being commissioned. It is located in the Main Injector tunnel, above the Main Injector and is a permanent magnet pbar storage ring at 8.9 GeV/c. It will use a combination of Stochastic Cooling and eventually Electron Cooling of the stored pbars. It has 2 major roles. First, pbars from the Pbar Source will be transferred to it at intervals of about 30-90 min. This will allow the Accumulator to always run with small stack sizes (less than about 20 to 40e10), where it is most efficient. Second, at the end of a store in the Tevatron, rather than throw away the remaining pbars, we will attempt to decelerate and recover them in the Recycler. If the Recycler works as designed, it will provide a large increase in the supply of pbars. However, another of the big questions for Run II is how well will the Recycler work and how efficiently will we be able to recover and re-use the pbars remaining at the end of a store?

Recycling the pbars requires a lot of effort for the other machines as well. Previously at the end of a store in the Tevatron, we could just fire the abort kickers, dumping

* Email: ppb@fnal.gov
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both the protons and the pbars. Now we will have to take the beams out of collision and quickly remove the 36*(240.e9) = 8.6e12 protons without quenching. (We will use a set of collimators in the E0 straight section to scrape away the protons. To direct the spray away from the cold magnets, we have installed 4 warm conventional magnets here to make a dogleg. The movement of the collimators will be computer controlled and will use fast feedback on local loss monitors.) Once the protons are gone, we will turn off all the separators, return from the low beta optics to the injection optics and decelerate the pbars to 150 GeV. They will then be transferred to the MI and decelerated through transition and down to 8 GeV. In order to get the large longitudinal emittance pbars through transition, they will change from the 53 MHz RF used above transition to the 2.5 MHz RF system previously used only for coalescing. Finally the pbars will be transferred to the Recycler and cooled for use in a later store.

2.3 Changes for the Tevatron

There are many upgrades and changes for the Tevatron :

• 36 X 36 bunches (396 nsec bunch spacing)

• pbar recycling

• 1 Tev upgrade. This is important to the experiments as a 10% increase in beam energy corresponds to an increase of about 30% in top quark production. We will be using the cold compressors to selectively (on a house by house basis) reduce the operating temperature of the ring. We are also shuffling magnet locations to put weaker magnets in colder locations. Also we are putting in prototypes for high T_C superconductor power leads and recoolers in spool pieces to improve the heat transfer between the 1 phase and the 2 phase helium.

• use of the Main Injector

• no ramps between stores to reset hysteresis and persistent currents. This used to take about 30 min. We want to skip this in order to reduce the time it takes to put in a store. Although conceptually simple, this requires accurate predictions of the size of any hysteresis effects and of the time dependent persistent currents on both the front and the back porch. The persistent currents depend upon the time spent at flattop and on the front and back porches and may "remember" several previous stores.

• different "Approach to Collisions". In Run IB, we brought the beams into collision longitudinally. We used an RF manipulation (cogging) to longitudinally move the pbars relative to the protons. This moved their crossing point from a region where they were separated to the IP where they collided head on. This method doesn't work with 36 bunches as there is no "cogging" where some proton and pbar bunches do not collide. For Run II, we will bring the beams into collision transversely, by collapsing separation bumps at the IPs. We believe this will be a slower process than before.

• new proton injection kickers. These new kickers will have a rise time of less than 396 nsec, the minimum bunch separation.

• new collimation scheme. In Run I, scraping the halo off the beams at the start of the store was a manual process that took about 30 min. For Run II, we have new targets and collimators which form a 2 stage collimation system. We aim to do this in about 5 min. with an automated process using feedback from beam loss monitors just downstream of the collimators. A separate set of collimators will use a similar system to quickly remove all the protons at the end of a store. (Firing the abort kickers would also kill the pbars, which we hope to recycle.)

• new "feed down sextupole" circuits. At locations where the protons and pbars are separated, we use sextupoles and skew sextupoles to act as quads and skew quads with opposite effects on the two beams. In Run I, we had circuits to adjust the horizontal and vertical tunes and one component of the transverse coupling. For Run II, we are adding another circuit that will adjust the other component of the transverse coupling that affects the minimum tune split.

• New Transverse and Longitudinal Damper systems. With the increase in the number of bunches, we are concerned about multi-bunch instabilities. These damper systems will probably use a combination of several narrow band channels (to damp individual modes) and a weak wide band system.

• new tune measurement system. The standard system in use during Run I looked at all the beam. There were some mechanisms in place to try to null out the proton signal so that we could see the pbar tunes. However, delicate tuning of the system was required for this and so typically we could not distinguish the pbar tunes during normal operation. The new system will allow us to easily see the tunes of individual proton or pbar bunches. It will also allow us to do "transfer function" style measurements, lightly exciting any bunch and observing its response.

• slightly different separator configuration. We have moved one horizontal separator and since the injection point into the Tevatron has moved from E0 to F0, the injection helix has also changed slightly.

• slight differences in the lattice. The D0 experiment is adding Forward Proton Detectors for Run II. These require additional warm space outside of the final focus triplet magnets. To provide this room, we were able to find lattice solutions that did not use one pair of the low beta quads. These quads have been removed. Also there is a minor perturbation to the lattice in E and F sectors. This uses the tune quads to adjust the separation between the beams at one of the collimator stations.

• Luminosity Leveling. If we are doing very well with luminosity, but are not yet ready to go to the 132 nsec bunch spacing, an intermediate way to limit the number of interactions per crossing (IC) is to artificially reduce the luminosity at the start of a store. We propose to do this by starting the store at a larger value for the β^*. As the store progresses and the luminosity falls (due to emittance growth and loss of beam), we can reduce the β^*, increasing the luminosity to its earlier levels. Although this keeps the IC at a more reasonable level, it also reduces the integrated luminosity delivered to the experiments.

• new method for controlling the low beta squeeze. This is required for Luminosity Leveling. Basically rather than doing the low beta squeeze as a time table triggered by an event, we will broadcast a parameter (on an MDAT frame) that tells the many control cards and power supplies where we are in the squeeze.

• faster shot setups. In Run I, it typically took about 3 hours to put in a store. For Run II, we want to reduce this to 30-60 minutes.

• new Collider Data Acquisition software.

Before they work well, each of these will require significant effort and machine time. Most of the Engineering Run and much of the Commissioning Run will be devoted to these projects.

3 EARLY RUN II (36 X 36)

The filling pattern has a 3 fold symmetry. For each beam, the 36 bunches are in 3 trains of 12 bunches. The trains are separated by abort gaps of 2.617 μsecs and within a train the bunches are separated by 396 nsec. This corresponds to a bunch spacing of 21 RF buckets.

Because the bunches are **not** evenly spaced around the ring, different bunches within a train encounter the bunches in the opposing beam at different places in the ring. This can cause differences between the bunches in a train. The 3 fold symmetry means that if all the bunches in the opposing beam are identical, then we only have to look for differences between the 12 bunches within a train. The 3 bunches at a given location (for example the second from the last bunch in the train) in the 3 trains should all behave identically. We will often refer to the bunches by their position in a train from 1 to 12.

3.1 Beam Beam Concerns

The main beam beam concerns for 36 bunch operations are :

• In all conditions from injection to the final collision condition, we have many more near misses through the arcs (about 70 instead of about 10). Also at this bunch spacing, there is an unfortunate coincidence that the distance between crossing points is almost exactly the cell length. There will be the same phase advances between many of a bunch's near misses. Also, between separators, the horizontal and vertical separations advance like the phase advances, and so the separations at many near misses will also follow a pattern. This will certainly drive certain families of resonances while suppressing others.

• 150 GeV lifetime - In Run IB, with frequent tuning, we could typically keep about a 13 hour lifetime for the pbars in the presence of protons. For Run II, the new damper systems and better control and understanding of the persistent current effects should allow us to greatly reduce the large (20-30 units) chromaticities at 150 GeV. These were known to cause lifetime problems but were used to prevent/control instabilities either while we were at 150 GeV or at the start of the ramp. Also for Run II, we expect to spend less time at 150 GeV (faster shot setups) which will reduce the effects of a poor 150 GeV lifetime.

• the transition from the injection to the collision helix. For certain reasons, we cannot use the same separation scheme in the injection and in the low beta optics. We change from the "injection helix" to the "collision helix (with separation bumps at the IPs)" part way through the low beta squeeze. Given the placement of the separators and the phase advances between them, we believe that it is inevitable that at some point during this transition, through some section of the ring, there is a region of poor separation. We can make this region short, but there are still several points where the beams will briefly (several seconds) collide at very small separations.

The Run I experience gives us some hope that this may be tolerable. At that time we were unaware of this problem. In Run I, there were many fewer bunches, but this poor separation extended over a much larger region, again resulting in several crossing points with poor separation. Despite this we rarely had problems with emittance blow up or beam loss during the transition from the injection to the collision helix.

If this becomes a major problem in Run II, we have a plan to inject into optics with a smaller β^* so that we can use the collision helix in our injection conditions.

• bringing the beams into collision. This was already briefly discussed as the Approach to Collisions.

• At the first "near misses" on either side of the interaction points, we do not have as much separation as we would like. This is shown in figures 1 and 2 below.

3.2 Separations Between the Beams

Figure 1 shows 4 views of the separation around the entire ring. The horizontal axis on each of these figures has units of half RF buckets. The harmonic number of the Tevatron is 1113, so the points shown are from 1 to 2226. These figures start just after, and end at the B0 Interaction Point. The D0 Interaction Point is at 742, 1/3 or 2/3 of the ring from B0. Protons travel in the direction of increasing half bucket number on this graph. Pbars travel in the opposite direction. Crossing points for the first pbar bunches in the 3 trains are marked by squares, for the 6th pbar bunch by asterisks, and for the last (12th) pbar bunch by diamonds. The bottom and 2nd from the bottom figures show the center to center horizontal and vertical separation between the pbars and the protons. The signs of these separations are for the displacements of the pbars relative to the center of the proton bunches. The second figure from the top shows the diagonal separation, the quadrature sum of the horizontal and the vertical separation, that is $\sqrt{x^2+y^2}$, where *x* and *y* stand for the horizontal and vertical separations, respectively. The top figure shows the diagonal sigma separation (dss), that is the $\sqrt{\left(x^2/\sigma_x^2\right)+\left(y^2/\sigma_y^2\right)}$. The σ's used in the top figure assume a beam energy of 1 TeV, transverse normalized 95% emittances of 20 π mm-mrad and fractional momentum spreads of 0.087e-3.

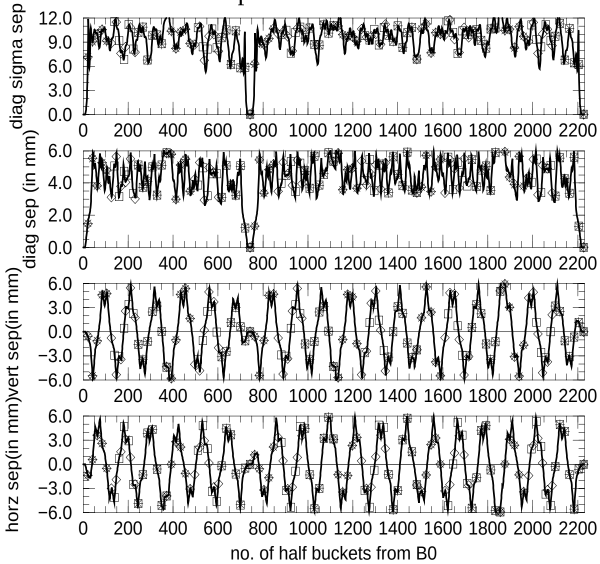

Figure 1 : Four views of the separation around the ring for 36X36. The CDF Experiment is at B0 which is at 0 and 2226 in the figure. The D0 Experiment is at D0 which is at 742 in the figure. From bottom (a) to top (d) : (a) Horizontal separation (in mm), (b) Vertical separation (in mm), (c) Diagonal separation (in mm), (d) Diagonal Sigma separation. Version: v3h15av2.cf045b.nppn2.

Of particular concern in figure 1 are the first crossing points on either side of the interaction points. At these points, the pbars have already passed the separators, but are still close enough to the separators so that there is little separation between the beams. Although the diagonal sigma separation (dss) does not appear much worse than many of the other points, the diagonal separation for these is well below all the others. We will see that the tune shifts (for pbars with zero betatron amplitudes) and the tune spreads (for pbars with a range of betatron amplitudes) from these points are much larger than those from all the other points. With the exception of the first and last bunches in the 3 trains, all the bunches meet bunches from the opposing beam at these points.

3.3 Tune Footprints

Figure 2 shows the tune spreads for pbars with a range of betatron amplitudes. This was calculated for bunch 6, in the middle of a train. These assume proton intensities of 270.e9/bunch and as for figure 1, these assume a beam energy of 1 TeV, transverse normalized 95% emittances of 20 π mm-mrad and fractional momentum spreads of 0.087e-3. Points are shown for pbars with betatron amplitudes of from 0 to 4 $\sigma_{\beta z}$ in steps of 0.5 $\sigma_{\beta z}$, where z may stand for either x or y. These figures assume that the pbars have no synchrotron motion. The fractional momentum spread is only used for the opposing proton beam. When we refer to a particle with a horizontal

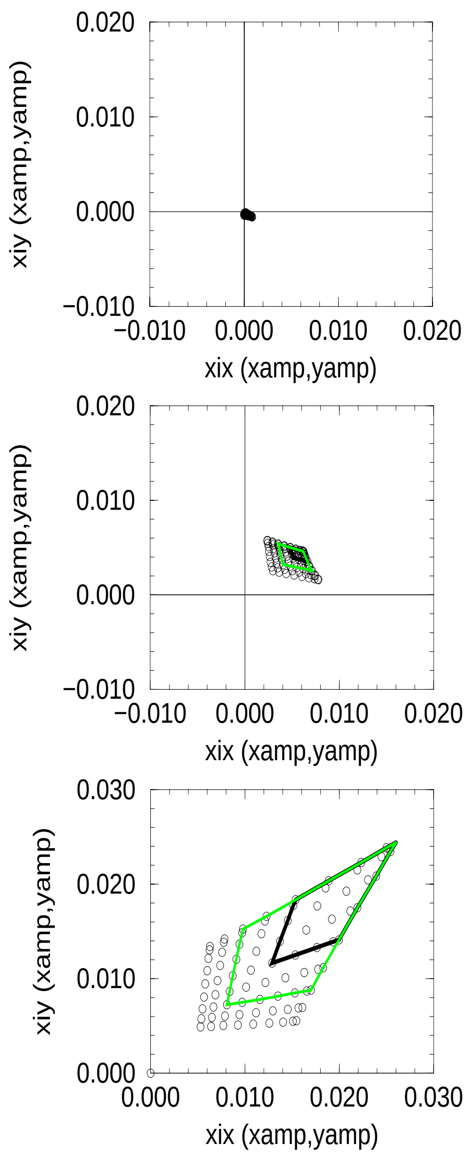

Figure 2: Tune footprints for 36X36, pbar bunch 6. From top (a) to bottom (c) : (a) Contribution from 66 crossing points. All crossings except for the IPs and crossing points next to the IPs. (b) Contribution from 70 crossing points. All crossings except for the IPs. (c) Tune Footprints including the effects of all 72 crossing points. Version: v3h15av2.cf045b.nppn2.

betatron amplitude of $\sigma_{\beta x}$, we mean a particle whose maximum horizontal displacement is $\sigma_{\beta x}$. As a guide to the eye, figures 2b and 2c also show contours at "$2\sigma_\beta$" and "$3\sigma_\beta$". For example the contour at "$2\sigma_\beta$" connects the points with horizontal and vertical betatron amplitudes of (0, 0) -> ($2\sigma_{\beta x}$, 0) -> ($2\sigma_{\beta x}$, $2\sigma_{\beta y}$) -> (0, $2\sigma_{\beta y}$) -> (0, 0).

Figure 2a shows the contributions to the tune spreads from 66 of the 72 crossing points. The only crossing points not included are the main IPs and the first crossing points on either side of the IPs. Both the tune shifts and the tune spread in figure 2a are very small. Figure 2b shows the contributions to the tune spreads from 70 of the 72 crossing points. In addition to all the points for figure 2a, this also includes the effects of the first crossing points on either side of the IPs. The effects from these 4 points are much larger than the combined effects of the other 66 points. This tune footprint has the same "sense" as a head on footprint, the zero amplitude particles are at the upper right, the pbars with large horizontal amplitudes and zero vertical amplitudes are at the upper left, etc. The horizontal tune shift and spread come almost entirely from the crossing point downstream (in the pbar sense) of the IP and similarly the vertical comes from the upstream crossing point. (The strengths of the quads are anti-symmetric about the IPs, so near the IP, the horizontal optics on one side become the vertical optics on the other side.)

The large tune spread suggests that these crossing points will also drive resonances strongly. Since the beams are separated at the first crossing points next to the IPs, these points can drive both even and odd order resonances.

We would like to improve the separation at these points, but there is little we can do. The separators are already running about as hard as they can. (If we increase the voltage on them, we believe they will spark much more frequently and a separator spark can ruin a store.) The separation could also be improved by modifying the optics in this region, for example by increasing the phase advance between the separators and these points. However we only have a few quads that are not on the main Tevatron bus and the optics through this region are already highly constrained. There is little we can do.

Finally figure 2c shows the tune spreads for all 72 crossing points, including the IPs. The tune shift parameter from **each** IP is .00989 and a comparison of figures 2b and 2c show that the total tune spread is still dominated by the effects of the IPs.

Figure 3 shows the tune spreads for all the pbar bunches in a train. Since the filling pattern is 3 fold symmetric, the 3 bunches at a given location (for example the second from the last bunch in the train) in the 3 trains should all behave identically, and we only have to look at 12 bunches.

The tune shifts for pbars with zero betatron amplitudes are shown as open circles. We have assumed gaussian distributions for the horizontal and vertical displacements and angles of the pbars, from these calculated their horizontal and vertical betatron amplitudes, and then interpolated between our previously calculated tune shifts with amplitudes to get the tunes for each pbar. The darker the spot in figure 3, the more pbars have those tunes.

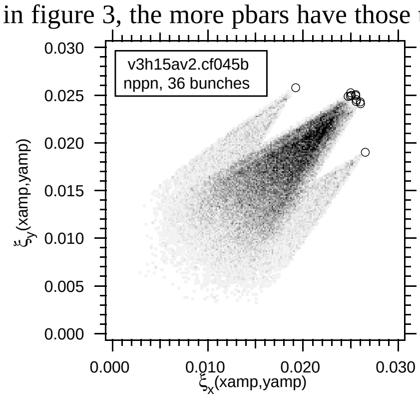

Figure 3: Gray scale plot showing the tune footprints for all 12 pbar bunches in a train for 36X36. The darker the point, the more pbars have those tunes. No synchrotron motion for the pbars. The open circles show the tunes for pbars in each bunch with zero betatron amplitudes.
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This figure shows that the tune footprints for most of the bunches are almost identical. However, pbar bunches 1 and 12 are shifted from the others because they do not see protons at the first crossing point upstream or downstream (in the pbar sense) of the IPs, respectively. As we saw earlier, these particular crossing points have much smaller separation and much stronger effects than any of the other crossing points (except for the IPs). As a result the pbars take up more space in the tune plane. This may make it more difficult to find operating conditions that are acceptable for all the pbar bunches. If this becomes an intractable problem, we are considering the possibility of not using (not filling) pbar bunches 1 and 12. This would give us stores of 36 proton bunches X 30 pbar bunches. There are other problems with this approach, but it is a possibility.

Figure 4 shows the tune plane near our normal operating point. This shows both even and odd resonances of up to 10th order. In Run IB, our nominal horizontal and vertical tunes in colliding beam conditions were about 0.581 and 0.576. These are the peaks for the proton tune lines on the spectrum analyzers. We believe that the pbar tunes were close to these, but the pbar tunes were never easily read. This operating point is between the 3/5=0.6000 and the 4/7=0.5714 resonances in figure 4. These resonances could have strong effects on the beams and we had to take care to stay clear of them. Not shown on this plot is the 7/12=0.5833. On some days, we felt we could see effects from this resonance, but on other days, it didn't seem to matter.

The lines shown in figure 4 are only part of the story. These show the locations of the resonances, but not their strengths or widths and not how these strengths and widths depend on a particle's betatron amplitudes. During Run I, the 3/5 seemed to generally be much stronger and much wider than the 4/7. If either of these resonances are much more strongly driven by the operating conditions for Run II, they may engulf the clear space between resonances. On the other hand, if part of the tune footprints overlap a resonance line, it may not be a problem depending on how strong that resonance is for the particular amplitudes of the particles with the tunes on the resonance.

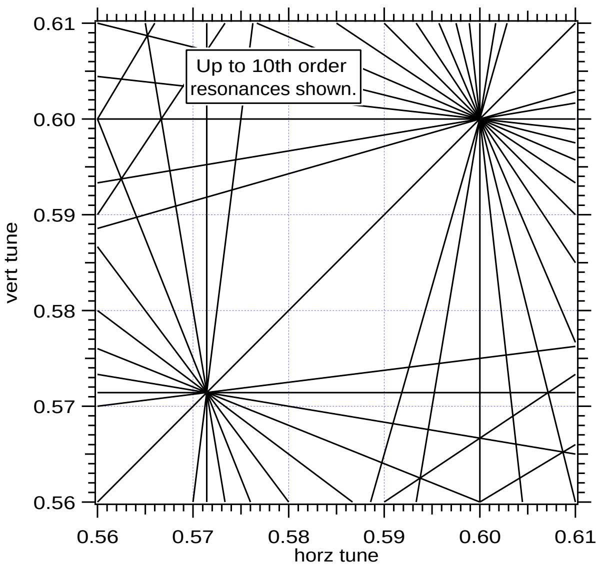

Figure 4: Resonance lines in the tune plane near our working point.

The two main resonances we are near, the 3/5 and the 4/7, are both odd and so, to lowest order, should **not** be driven by the beam beam interaction at the IPs. If the beams collide head on at the IPs, then the IPs should only drive these as 10th and 14th order resonances. But because the beams are separated at the first crossing points, those points can drive these as 5th and 7th order resonances. This is true for all the crossing points in the arcs, but we are more concerned about the first crossing points on either side of the IPs since the separation is small there and we have seen that they produce much larger tune shifts and spreads than the other crossing points. (To further complicate matters, the 3/5 and 4/7 will generally also be driven by the sextupole distribution.)

These are very simple calculations and very simple considerations, but they begin to hint at the problems involved. We would certainly like to have more detailed beam beam simulations and calculations to help us understand what we will see as we re-commission the Tevatron. (There are some efforts underway.) Although we will have many challenges, the 36 X 36 bunch conditions are similar enough to what we had in Run I that we are fairly confident we can make this work.

4 LATE RUN II (140 X 103 ?)

As Run II progresses, we expect the pbar stacking rates to increase and that we will start recycling pbars. With an increased supply of pbars and only 36 bunches, the number of interactions per crossing will also increase and again becomes an issue. As discussed earlier, luminosity leveling is a temporary fix, but has a significant cost in integrated luminosity. We are planning to eventually reduce the minimum bunch spacing to 132 nsec. This will allow us to put in about 140 proton bunches on about 103 pbar bunches.

4.1 Filling Pattern for 140 X 103

Assume for the moment that we keep the same basic filling pattern as for 36 X 36, except with 1/3 the bunch spacing. We do not plan to improve the abort kickers, so we need to keep the abort gap the same length. In each of the 3 trains, we would then have (3*11)+1 = 34 bunches, for a total of 102 bunches per beam.

The filling pattern for 36 X 36 is 3 fold symmetric with 3 abort gaps in each beam. But for the beam abort we only need 1 abort gap per beam. If we fill 2 of the abort gaps, we can fit in 2*19=38 more bunches per beam, for a total of 140 bunches per beam. The abort gaps in the 2 beams must meet at A0, the location of the abort. The D0 experiment is diametrically opposite A0, so the abort gaps would also meet there, giving D0 140 bunch collisions per revolution time. However at B0, the location of the CDF experiment, the abort gaps do not meet, and CDF would only see 121 bunch collisions per revolution time. We must treat the 2 experiments equally, so we choose to fill 2 abort gaps in the proton beam and only 1 abort gap in the pbar beam. This has 140 X 121 bunches and provides 121 bunch collisions per revolution time to both experiments. This means that most proton bunches will collide with a pbar bunch at both B0 and D0, but that 19 proton bunches will only collide with a pbar bunch at B0 **or** at D0. All the pbar bunches will collide with proton bunches at both B0 and D0.

Finally, we plan to upgrade the proton injection kicker to have a rise time of slightly less than 132 nsec, but the pbar injection kicker rise time will stay at just under 396 nsec. The flattop of the pbar kicker can accommodate 10 bunches at 132 nsec spacing, so after sets of 10 bunches, we have to leave 3 "empty 132 nsec slots" for the rise time of the pbar injection kicker. This reduces the number of pbars we can use and leaves us with 140 proton bunches X 103 pbar bunches.

The proton beam has only one abort gap, so all 140 proton bunches make up one long train. The pbar beam has 2 abort gaps, so there are 2 pbar trains, a short train containing 30 pbar bunches and 2 "injection gaps" and a long train containing 73 pbar bunches and 7 "injection gaps".

4.2 Crossing Angles

At a bunch spacing of 132 nsec, the first crossing points on either side of the main Interaction Points are **before** the electro-static separators. The second crossing points are just beyond the separators, but without a crossing angle, the separation at these points is only about 0.7 σ. Without a crossing angle, for each Interaction Point, we would have 3 head on collisions and 2 crossings with a separation of about 0.7 σ. This is unacceptable and so for this bunch spacing, we require a crossing angle. Unfortunately this requires large crossing angles.

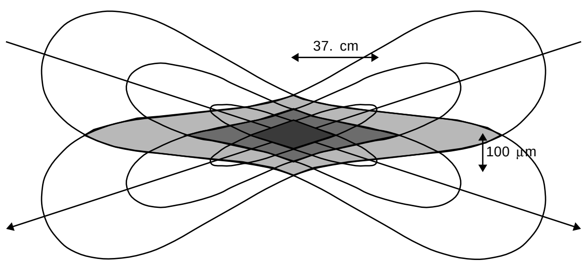

Figure 5: A sketch of two bunches crossing at an IP with β^* of 35 cm, bunch length of 37 cm, and half crossing angle per plane of 136 µrad, corresponding to about 4σ separation at the first parasitic crossing points. The direction of motion for the two bunches is indicated by the arrows and they are viewed from the angle where the separation appears largest. This drawing is to scale, however the horizontal and vertical scales are very different, causing the crossing angle to appear to be much larger than it is. 1σ, 2σ, and 3σ contours are shown with the shaded areas indicating the overlap of these contours.

For separations of about 3-5 σ at the first few crossing points, the crossing angle significantly reduces the bunch overlap at the Interaction Point, and hence the peak luminosity. The reduction in overlap is shown graphically in Figure 5, a sketch of 2 bunches colliding with our expected parameters, and in figure 6, a plot of the reduction in the peak luminosity with the crossing angle. The calculation used for the points in figure 6 includes both the hourglass effect (the reduction in luminosity due to the variation in the β over the bunch length) and the crossing angle. The dotted line in figure 6 ignores the hourglass effect. For our parameters, the crossing angle reduces the longitudinal extent of the bunch overlap, the "luminous region". It confines the overlap of the bunches to the region where β is very near its minimum and so the hourglass effect has little effect on the luminosity. Here the length of the luminous region is mainly determined by the transverse size of the beams at the IP and by the size of the crossing angle, **not** by the bunch lengths.

Since we have round beams, the loss in peak luminosity does not depend on the orientation of the crossing angle, only on its size. For reasons related to our specific lattice and to the separation at the first few crossing points near the IP, we choose to use equal horizontal and vertical crossing angles.

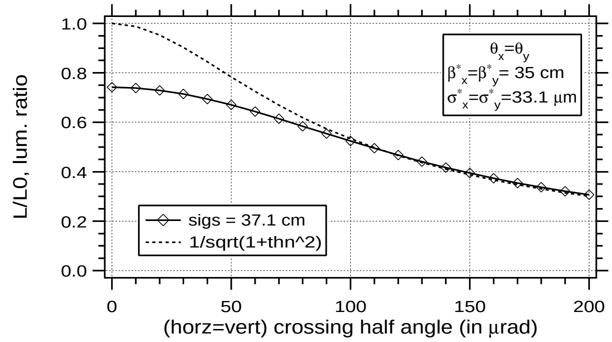

Figure 6: The dependence of the luminosity (L/L_0) on the crossing half angle in each plane. The points and the solid line include the hourglass effect. The dotted line shows the approximation that ignores the hourglass effect. $L_0 = (fBN_{prot}N_{pbar}/4\pi\sigma_{x0}\sigma_{y0})$, the luminosity if ($\beta^*$>> bunch length) and no crossing angles. This uses a bunch length of 37.1 cm.

The dramatic loss in peak luminosity is a strong incentive to keep the crossing angles as small as possible. But the crossing angle also essentially determines the separation at the first 2 crossing points on either side of the IPs. (This is a total of 8 crossing points.) With both these considerations in mind, we presently plan for half crossing angles of +-170 µrad in both the horizontal and the vertical plane. This gives a total angle between the beams of $2\sqrt{2}$ (170 µrad)=480 µrad and corresponds to separations of about 5σ at the first crossing points.

There are several implications of these large crossing angles :

- Loss of peak luminosity
- Integrated luminosity concerns
- Change in size and shape of the tune shift footprints from the main IP
- Synchro-betatron resonances driven by the beam beam interaction at the main IPs. Consider a particle with zero betatron amplitudes, but a non-zero synchrotron amplitude. When it arrives early at an IP, it will have a horizontal and a vertical displacement as it passes the longitudinal center of the opposing bunch. When it arrives late at an IP, it again has horizontal and vertical displacements, but now of the opposite sign. This correlation between its arrival time and its displacement will drive synchro-betatron resonances. The synchrotron tune for the Tevatron at 1 TeV is about 0.00073 (35 Hz), so the synchro- betatron lines are tightly clustered around the pure betatron resonances. The 2 resonances closest to our working point are both odd, the 3/5 and the 4/7 (see figure 4). The head on beam beam interaction can only drive these as 10th and 14th order resonances. With a crossing angle, the beam beam interaction at the IPs will drive the synchro-betatron lines off these resonances.

These synchro-betatron lines will be higher than 5th or 7th order, but lower than 10th or 14th.

• Strong effects from the first few crossing points. We will see that the tune spreads from these points are not small. Since the beams are separated, the beam beam interaction at these points can drive both even and odd resonances.

• Large displacements (2-3.5 mm) in the low beta quads. We have some evidence that the multipole content in these quads may cause problems with displacements of about this size. (This is the reason we are adding a new "feed down sextupole" circuit for Run II. But if the multipole content is a problem, this feed down circuit will only let us compensate one aspect of one multipole term.)

4.3 Integrated Luminosity Estimates

Figure 6 shows that we expect to lose about a factor of 2 in peak luminosity with a crossing angle. But this does **not** directly translate into a loss of integrated luminosity.

Estimates of the sustainable integrated luminosity depend on many factors related to how well the entire accelerator complex is working. A great many details of the performance of the accelerator complex are summarized as 2 parameters, the pbar stacking rate and the pbar recycling efficiency. Unfortunately, we don't yet have a clear idea of the values of these 2 parameters in Run II.

We will guess at these parameters (and several others) to make some estimates of the sustainable integrated luminosity for 2 conditions. The main tool for these estimates is a program that, given the initial beam and machine parameters, simulates the evolution of the beam intensities, beam emittances, and the luminosity during a store. This code was originally written by D. Finley [3] and includes 3 effects :

• Intra-Beam Scattering (IBS). This blows up the longitudinal and horizontal emittances. Coupling is assumed to split the horizontal emittance growth equally into the horizontal and vertical planes, keeping the horizontal and the vertical emittances equal.

• Beam loss from "Luminosity" Events. It uses the total cross section (elastic + inelastic) for particles lost from the beam and uses only the inelastic cross section for the number of interactions per crossing.

• Vacuum effects. These are weak compared to the other two.

J. Marriner later modified this code to include the effect of crossing angles on the luminosity and a recycling efficiency that depends on the pbar emittances at the end of the store.

This code does **not** make any attempt to include effects from the beam beam dynamics. It **assumes** that we can find "good" operating conditions where the beam beam effects are weak compared to the other effects it does include. While this was true for Run I, where we had only 6 X 6 and no crossing angles, we are not confident that this will be the case for late Run II. As a result, the estimates of the integrated luminosity below, particularly for the case with a crossing angle, may be very optimistic.

We will make estimates for 2 different conditions.

Condition 2 has 396 nsec bunch spacing, 36 X 36 bunches, and if necessary, the luminosity is leveled to be less than 1.7e32/(cm^2 sec). This corresponds to less than 5 interactions per crossing on average.

Condition 9 has 132 nsec bunch spacing, 100 bunch collisions per turn at each detector (this is very close to the 103 we would get with the 140 X 103 filling pattern), +-170 μrad half crossing angles in the horizontal and vertical planes, and if necessary, the luminosity is leveled to be less than 3.8e32/(cm^2 sec). This corresponds to less than 4 interactions per crossing on average.

For both of these conditions, we assume a 1 hour shot setup time during which we are not stacking and a 20% loss in getting pbars from the Accumulator to colliding beam conditions in the Tevatron.

Table 1 : Integrated Luminosity Estimates

Stack Rate (e10/hr)	Recyc. Effic.	Cond.2 ave.lum. 1/(pb hr)	Cond.9 ave.lum. 1/(pb hr)	diff.
20	0	0.389	0.221 (1.2)	-43%
20	60%	0.487	0.385 (2.5)	-21%
20	80%	0.525	0.434 (2.5)	-17%
40	0	0.518	0.516 (3.6)	0%
40	60%	0.548*	0.685 (4)	+25%
40	80%	0.548*	0.761 (4)	+39%

* means that there is a surplus of pbars
diff. = (Cond.9-Cond.2)/(Cond.2)

The ave. lum. in Table 1 is the luminosity (averaged over a store) that we can maintain with the stated stacking rate and recycling efficiency. The "pbar economics" are included in these. For Condition 9, the average number of Interactions per Crossing at the start of a store is shown in parenthesis next to the average luminosity. All of the cases for Condition 2 stores start at their luminosity limit of 1.7e32/(cm^2 sec) with an average of 5 Interactions per Crossing.

When the Recycler works and the pbar stack rate is above about 20 or 25e10/hr, we do not lose too much integrated luminosity with 132 nsec. In these conditions, the change to 132 nsec will either cut the number of IC by about a factor of 2 or increase the integrated luminosity. Again this assumes that we can find "good operating conditions" for 132 nsec bunch spacing.

4.4 Separations Between the Beams

Figure 7 shows 4 views of the separation around the entire ring with +-170 μrad horizontal and vertical crossing half angles at each IP. This shows the same quantities and the same setup as figure 1 except that here the squares mark the crossing points for a pbar bunch near the middle of the short train and the diamonds for a pbar bunch near the middle of the long train.

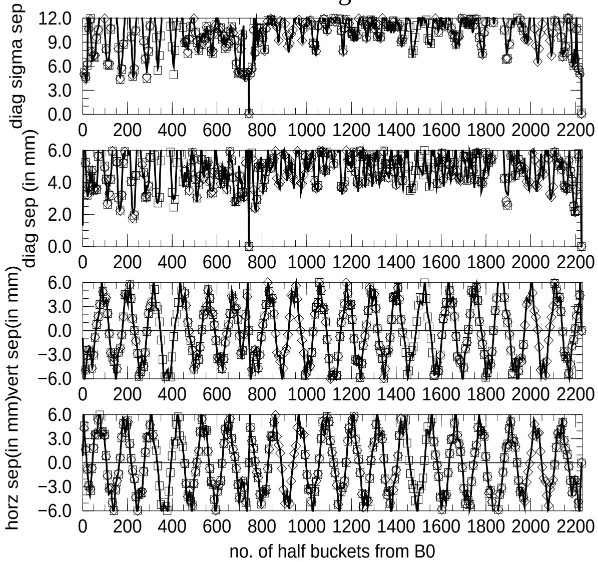

Figure 7 : Four views of the separation around the ring for 140X103. The CDF Experiment is at B0 which is at 0 and 2226 in the figure. The D0 Experiment is at D0 which is at 742 in the figure. From bottom (a) to top (d) : (a) Horizontal separation (in mm), (b) Vertical separation (in mm), (c) Diagonal separation (in mm), (d) Diagonal Sigma separation.
Version:v3h15av2.cf045b,sb4(a0h),a103a,nppn.170pnpn2

The crossing angles completely determine the separation at the first crossing points on either side of the IPs. At the second crossing point, the kick from the separators does have some influence and, depending on the relative sign of this kick and the crossing angle, this can either increase or decrease the separation. At the third crossing point, the separations from the crossing angles and the separators are similar in size and so the relative signs are important. There are many combinations of the signs for the crossing angles and the signs of the separators, but there are also some constraints on these. Figure 7 shows one of our favorite configurations.

In figures 7c and 7d, in the region from about 100 to 420 half buckets from B0, there are several crossing points with relatively "poor" separation. These dips in the diagonal separation are caused by the horizontal and vertical separations being too close in phase. Ideally, they should be $\pi/2$ out of phase, so that the horizontal separations are near a maximum when the vertical separation is near zero and vice versa. Other crossing angle configurations with different signs for the crossing angles have better separation in this region, but slightly worse separation at some of the points near the IPs. We believe that the configuration in figure 7 may be a good trade off, because the tune spreads due to these points in the arcs remain small. (See figure 8a. The βs in the arcs are smaller than the βs at the first few crossing points.)

4.5 Beam Beam Dipole Kicks

Each time a bunch encounters a bunch from the opposing beam, they both receive kicks. If the beams are separated, then the average kick received by the bunch will be non-zero. The average kicks received by both beams will change their orbits and hence their separation. The change in separation in turn changes the average kicks the bunches give each other. This is an involved problem to handle correctly, as each bunch encounters the other beam in different places. We make 2 approximations to this problem. First we assume that the proton bunches do not move and use the sum of the proton and the pbar intensities for the kick given to the pbar bunch. (The pbar intensities are expected to be about a factor of 4 less than the protons.) Second we use the kick given to a zero amplitude pbar as an approximation to the average kick given to all the pbars in that bunch.

After calculating the changes to the separations, we adjust the separator settings to fix the average effect at the IPs on all the pbar bunches. Of course, this change in the separators changes the separations which in turn changes the beam beam dipole kicks. It typically takes 2 iterations to get this right. Even after we have corrected the average effects, there are still bunch to bunch variations.

For 36 X 36, both the changes to the separator settings and the remaining bunch to bunch variations were fairly small. After adjusting the separators, the separations at the IPs were less than 1.5 μm (for our nominal parameters, the beam size at the IPs is 33.1 μm) and the total crossing angles were less than 11 μrad.

For 140 X 103, these beam beam dipole kicks have much larger effects. The maximum separation at the IPs is 7 μm and the rms separation is 1.6 μm. Considering only the pbar bunches in one train or the other, the rms variation in the crossing angles at the IPs is about 3 μrad. But there are also systematic differences between the crossing angles for pbar bunches in the long and the short trains. At B0, this systematic difference is almost purely horizontal, at D0, it is almost purely vertical. At B0, the average horizontal crossing angle for pbar bunches in the long train is about 333. μrad and for pbar bunches in the short train is about 356. μrad, a difference of 23. μrad. At D0, the average vertical crossing angle for pbar bunches in the long train is about -332. μrad and for pbar bunches in the short train is about -358. μrad, a difference of 26. μrad. (For both of these, the desired magnitude of the crossing angles is 2*170 μrad=340. μrad.)

These are large enough to concern us and merits further investigation, but we aren't sure what we can do about it.

4.6 Tune Footprints

Figure 8 shows the tune spreads for pbars with a range of betatron amplitudes. This was calculated for pbar bunch

152, in the middle of the long train. This uses the same parameters as figure 2.

Figure 8a shows the contributions to the pbar tune spreads from 262 of the 280 crossing points. The only crossing points not included are the main IPs and the first 4 crossing points on either side of the IPs. Both the tune shifts and the tune spread in figure 8a are very small. In figure 7, we saw several crossing points with relatively "poor" separation in the region from about 100 to 420 half buckets from B0. The contributions of these points are included in figure 8a and are small.

Figure 8b shows the contributions to the tune spreads from 278 of the 280 crossing points. In addition to all the points for figure 8a, this also includes the effects of the first 4 crossing points on either side of the IPs. The effects from these 16 points are much larger than the combined effects of the other 262 points. This tune footprint has the opposite "sense" as a head on footprint, the zero amplitude particles are at the lower left, the pbars with large horizontal amplitudes and zero vertical amplitudes are at the lower right, etc.

The area enclosed by the "$3\sigma_\beta$" contour is fairly small, but the tune spread increases substantially if pbars out to "$4\sigma_\beta$" are included. This is not surprising since there is about 5σ separation at the first crossing points. Pbars with amplitudes of 4σ are starting to explore the beam beam kicks at 1σ from the center of the opposing beam. This is where the kicks are strong and very non-linear.

The large tune spread suggests that these crossing points will also drive resonances strongly. Since the beams are separated at the first crossing points next to the IPs, these points can drive both even and odd order resonances.

Figure 8c shows the tune spreads and shifts from one of the two interaction points. We have shown it at twice the scale to ease comparison with the other contributions. This calculation uses a bunch length (longitudinal sigma) of 37.1 cm and a transverse beam size (sigma) of 33.1 μm. Both the size and the shape are modified from the head on footprint. If there were no crossing angle, the tune shift for zero amplitude particles is .00989. The decrease in the overlap reduces this by more than a factor of 2. The shape of the footprint is also much narrower. The changes in the tune spreads suggest changes to how the beam beam interaction at the main IPs drives resonances.

Figure 8d shows the total tune shifts and spreads for all 280 crossing points. These are significantly smaller than the footprints shown in figure 2c for the 36 X 36 case. There are 2 main reasons for this. First, the tune spreads from the main IPs are greatly reduced by the crossing angle. Second, the footprints shown in figure 8b, which are almost entirely due to the first few crossing points on either side of the IPs, have the opposite sense as the footprints from the main IPs, leading to some cancellation and compression of the total tune spreads. Although not immediately evident, the footprint in figure

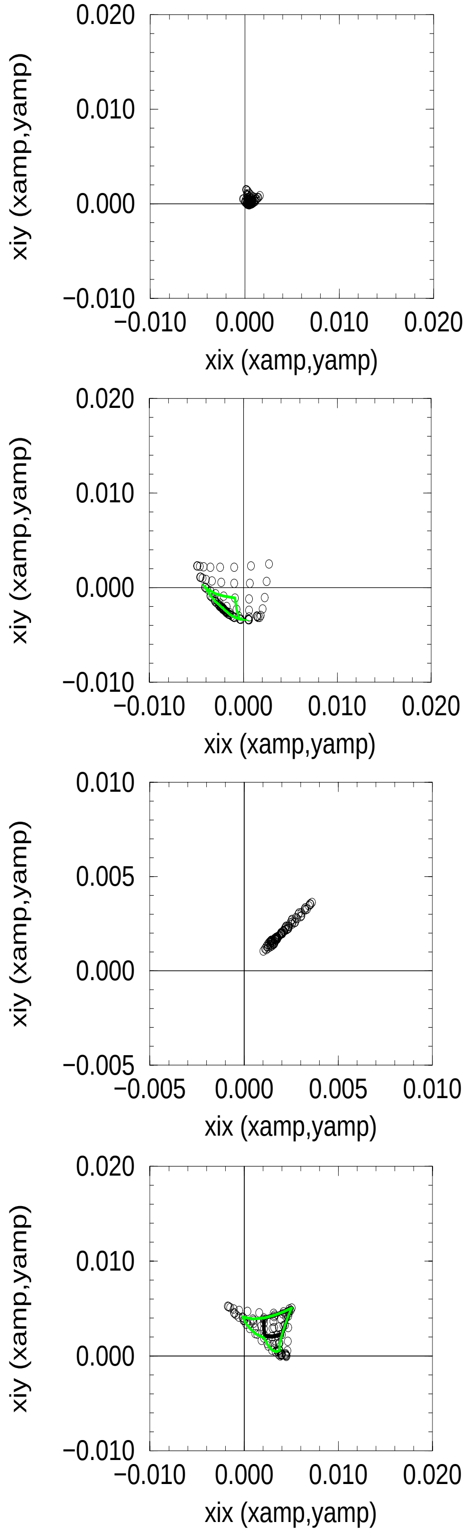

Figure 8: Tune footprints for 140X103, pbar bunch 152. From top (a) to bottom (d) : (a) Contribution from 262 crossing points. All crossings except for the IPs and the first 4 crossing points on either side of the IPs. (b) Contribution from 278 crossing points. All crossings except for the IPs. (c) Tune footprint from one of the two IPs only. Note the different scale. (d) Tune Footprints including the effects of all 280 crossing points.
Version: v3h15acsb4a103a.nppn.170pnpn2.

8d is "folded". Pbars with horizontal and vertical betatron amplitudes of about ($4\sigma_{\beta x}$, $4\sigma_{\beta y}$) have about the same tunes as those with betatron amplitudes of (0, 0). For small amplitude particles, the tunes decrease with increasing amplitude due to the main IPs and the tune changes due to the first few near misses are small. For larger amplitude particles, the tunes increase with increasing amplitude due to the first few near misses and the tune changes due to the main IPs are small. Taken together, the competition between these effects leads to the fold in the footprint.

On the good side, these folds mean that the beam occupies less area in the tune plane and **if the resonances have not become stronger and wider,** we may have more room in the tune plane between resonances. On the bad side, the folds mean that a particle can have a larger amplitude range for a given range of its tunes. Certain amplitude particles will not detune off of resonances as quickly and so a resonance that aligns properly with the fold could cause a greater amplitude change than it could without the fold. We tend to view these folds as a bad sign and as an indicator of strong non-linearities, but we don't know if these views are justified.

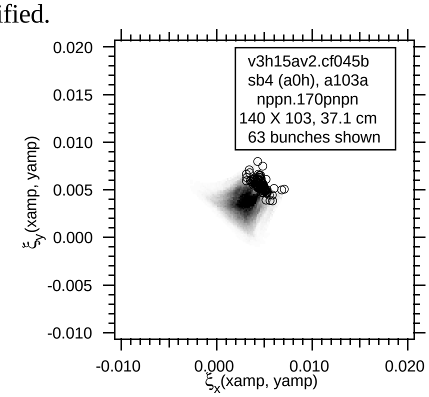

Figure 9: Gray scale plot showing the tune footprints for 63 representative pbar bunches for 140X103. All the bunches in the short train are shown. About 10 bunches from the beginning, middle, and end of the long train are shown. The darker the point, the more pbars have those tunes. No synchrotron motion for the pbars. The open circles show the tunes for pbars in each bunch with zero betatron amplitudes.
Version: v3h15av2.cf045b.sb4a103a.nppn.170pnpn2

Figure 9 shows the tune spreads for 63 representative pbar bunches. Each of the 30 pbar bunches in the short pbar train are shown as well as about 10 bunches from the start, middle, and end of the long pbar train. Because we don't have any symmetry in the 132 nsec filling pattern, no two pbar bunches encounter the protons at exactly the same set of crossing points and generally every pbar bunch has a slightly different footprint.

The spread between bunches is smaller here (in figure 9) than for 36 X 36 (in figure 3). This is mainly because the crossing angles have improved the separation at the first few crossing points on either side of the IPs.

4.7 Hardware Requirements

Surprisingly little new accelerator hardware is needed for 132 nsec operation.

• More pulsers/power supplies for the proton injection kicker. The proton kicker that is presently being installed can be used for either 396 nsec operation or 132 nsec operation. The magnet is composed of 5 modules. For 396 nsec, we will have 2 sets of positive and negative pulsers/power supplies. One set will power 2 modules, the other set will power 3 modules, giving a rise time of slightly under 396 nsec. For 132 nsec operation, each module will have its own set of pulsers/power supplies, giving a rise time of a little under 132 nsec.

• More separators. Although we can make crossing angles with our present complement of separators, a few additional separators will greatly expand our options for the signs on the crossing angles. This is important because at some of the first few crossing points near the IPs, the separations due to the crossing angles and due to the separator kicks are similar and the relative signs determine whether these add or subtract from each other. We are ordering 1 new horizontal separator module and 3 new vertical separator modules. These will be run off of existing power supplies.

• Coalescing upgrade for the Main Injector. The present coalescing system uses 2.5 MHz RF. If we attempt to coalesce multiple proton bunches at the same time, they will have 396 nsec bunch spacing. For 132 nsec operation, we have to change the fundamental frequency for coalescing to 7.5 Mhz, and add a second (15 MHz) and a third (22.5 MHz) harmonic. The higher harmonics are needed to make the RF waveform more linear over the 5 53 MHz buckets that contain beam.

• Damper work. With many more bunches at a closer bunch spacing, we may see new multi-bunch modes causing problems and need additional narrow band feedback channels to control them. We may also require an upgrade of the weak wide band feedback systems.

• Instrumentation Upgrades. Much of the present instrumentation will have to be upgraded to deal with the many more bunches and the more closely spaced bunches. We will also have to learn how to deal with the tremendous amounts of returned data.

We do not believe that any of these technological issues will present serious problems.

4.8 Conclusions

The 132 nsec bunch spacing with large crossing angles at the IPs is not guaranteed to work. We are very concerned about the synchro-betatron resonances driven by the beam beam interaction at the IPs and by the possible strong effects from the first few near misses on either side of the IPs. We are also concerned about the further increase in the number of crossing points in the arcs and the resulting increase in the size of effects from the beam beam dipole kicks.

We suspect it will be a challenge to find good operating conditions and, if we can find them, they may be quite different from what we used for either Run I or 36 X 36 bunch operation.

5 CROSSING ANGLE STUDIES

5.1 Specifics

With the above uncertainties about 132 nsec bunch spacing, an important study is to simply try putting in a large crossing angle with either a 36 X 36 store or a 2 X 1 store. This would be a very direct test of the concerns about the synchro-betatron resonances. (However, even if we find good conditions in these studies, that is not a guarantee that 132 nsec will work. There are still concerns about the small separation at the first near misses and the very large number of near misses around the ring. Also, the problem may not be any of these individually but may be how these effects **combine/interact**.)

We will be installing additional separator modules for 132 nsec operation. However, even with the present complement of separators, for one particular set of signs of the crossing angles, we can make large crossing angles at the IPs. The resulting separations around the ring are shown in figure 10.

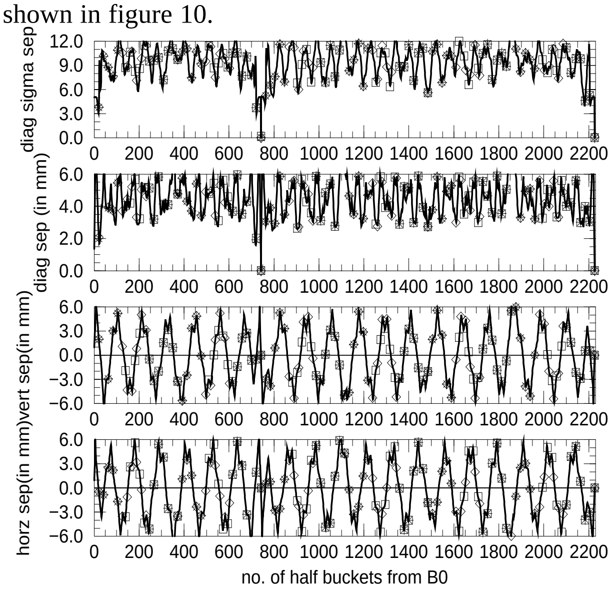

Figure 10 : Four views of the separation around the ring for crossing angle study with 36X36. The CDF Experiment is at B0 which is at 0 and 2226 in the figure. The D0 Experiment is at D0 which is at 742 in the figure. From bottom (a) to top (d) : (a) Horizontal separation (in mm), (b) Vertical separation (in mm), (c) Diagonal separation (in mm), (d) Diagonal Sigma separation.
Version: v3h15av2 sa1 (d48h) nppn.170ppnn2.

Since we are proposing this as a study during 36 X 36 operations, the markers on figure 10 show the crossing points for 36 bunches, as was done in figure 1.

Comparing figure 10 to figure 7, in figure 10 the separation through the arcs is good, but there is a crossing point near each of the IPs (at 21 and 721 half buckets from B0) where the separation is not as large as we would like. (We may be able to improve these points slightly.) This shows the difference in separation that can result from a different choice of signs on the crossing angles.

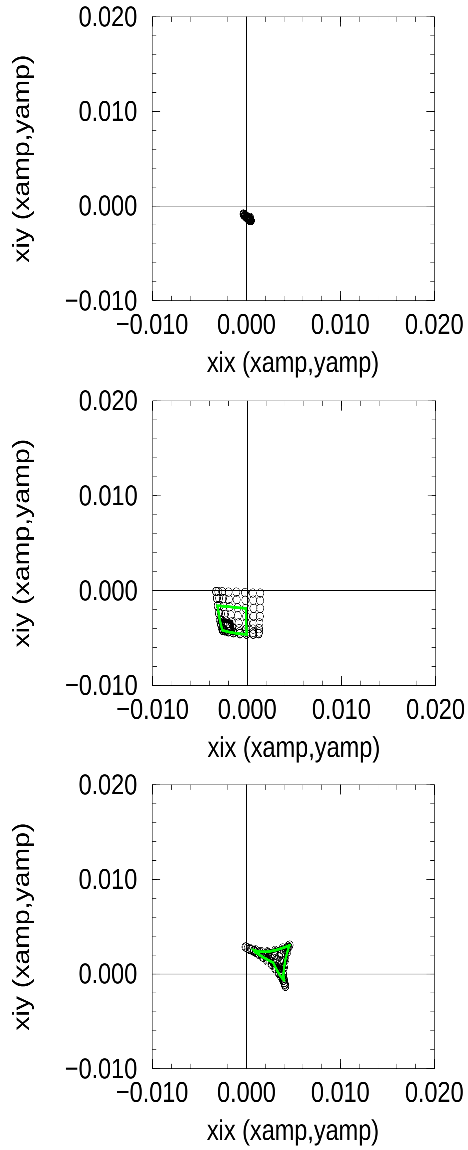

Figure 11: Tune footprints for crossing angle study with 36X36, pbar bunch 6. From top (a) to bottom (c) : (a) Contribution from 66 crossing points. All crossings except for the IPs and crossing points next to the IPs. (b) Contribution from 70 crossing points. All crossings except for the IPs. (c) Tune Footprints including the effects of all 72 crossing points.
Version: v3h15asa1.nppn.170ppnn2.

Figure 11 shows the tune footprints for pbars with a range of betatron amplitudes. This was calculated for pbar bunch 6, in the middle of a train, and uses the same parameters as figure 2. Figure 11a shows the contributions from 66 of the 72 crossing points. The only crossing points not included are the IPs and the first crossing points on either side of the IPs. As usual, the tune shifts and the tune spreads are very small. Figure 11b shows the contributions from 70 of the 72 points. The only crossing points not included are the 2 IPs. As in figure 8b, this tune footprint has the opposite "sense" as a head on footprint. Even with only 36 bunches, the effect of the first crossing points are more similar to the 140 X 103 case.

The contributions to the tune footprints from the IPs is the same as was shown in figure 8c. Finally, figure 11c shows the total tune shifts and spreads from all 72 crossing points. The size and shape are similar to what we saw in figure 8d for 140 X 103 bunches.

Although there are still important differences between this 36 bunch study and the 132 nsec operation, this encourages us that the study may be a good test of some of the 132 nsec problems.

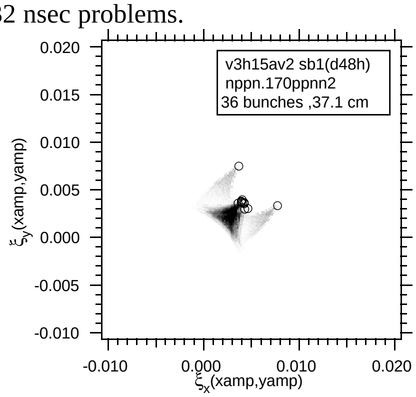

Figure 12: Gray scale plot showing the tune footprints for all 12 pbar bunches in a train for crossing angle studies for 36X36. The darker the point, the more pbars have those tunes. No synchrotron motion for the pbars. The open circles show the tunes for pbars in each bunch with zero betatron amplitudes.
Version: v3h15asa1.nppn.170ppnn2

Finally figure 12 shows the tune shifts and spreads for all 12 pbar bunches in a train. As in figure 3, the footprints for 10 of the 12 bunches are nearly identical, but the first and last bunches in the train are different because they do not see protons at the first crossing point upstream or downstream of the IPs.

This looks like a worthwhile study to get an early view of how difficult 132 nsec bunch spacing will be. Because no special equipment is needed, we could try this as soon as the Commissioning Run in Fall 2000.

Although this is presented as a study, depending on what we find, it may be more of a long development process. We may use these conditions to try to diagnose our problem and to test possible solutions or tuning algorithms.

5.2 Generalities

How would we go into this study ? For now assume that we do this as end of store studies. (Later we will have some comments on the relative advantages of doing end of store vs. dedicated studies.)

- Start from head-on colliding beam conditions (1 Tev, β^*= 35 cm, 36 X 36 bunches).
- Turn up the horizontal and the vertical crossing angles together until the losses or lifetimes get bad.
- Re-tune to try to bring down losses and/or improve the lifetime. There are many things to try : Separation bumps at the IPs (Our "crossing angle" bumps may have slight errors that change the separation at the IPs.), tunes, chromaticity, coupling, orbit bumps, cogging, possibly the sextupole distributions and/or octupoles, etc. We may also have to re-scrape the beams to remove any halo that we generated while at small crossing angles or while we were changing the crossing angles.
- If successful, continue increasing the crossing angles. We want to try to get out to angles of about +-136 μrad/plane or +-170 μrad/plane.
- Depending on how often we have to re-tune, we may just try "jumping" to these angles.
- If things are really bad, maybe try again with smaller proton intensities or larger β^*.

There are some games we can play to try to separate the contributions from different mechanisms, but the combinations may be important.

- The strengths of the synchro-betatron resonances from the main IPs can be varied by varying the size of the crossing angle.
- The effects of being off-center in the low β quads are also linked to the size of the crossing angle. **IF** there is enough aperture in these quads, we could try to center the pbars and push the protons twice as far off the centerline.
- How do the resonance driving terms from the 2 Interaction Points (B0 and D0) combine ? We may be able to get a very rough, general feel for this by comparing 2 X 1 stores with 1 X 1 stores. For the 1 X 1 stores, we can adjust the cogging so that the bunches collide at B0 or at D0. For a 2 X 1 store, we would be set up so that the single pbar bunch collides with one of the proton bunches at B0 and with the other at D0.
- First few near misses. These are not an issue in a dedicated 2 X 1 store. With 36 X 36 bunches, there are 2 crossing points with diagonal σ separation of only about 3.7. In some ways (tune spread from the first few near misses, size and shape of the tune footprint for all collisions), this is similar to what we would have for 132 nsec bunch spacing. However in many other ways, the situations are quite different (2 "bad" points vs. several). This may give us some idea of the problems, but

it is a significant difference between the studies and the real 132 nsec situation.

• Beam beam dipole kicks. These are very small with 2 X 1 stores and are still small with 36 X 36 stores. With 140 X 103 bunches, these become more of a problem. Again, this is a significant difference between the studies and the real 132 nsec situation.

• Larger β^*. This reduces the divergence at the IP by 1/sqrt(β^*), so less crossing angle is needed for a given separation at the first near misses. Also it makes the σ^* larger by sqrt(β^*). For the same separation at the first crossing points, the parameter ($\delta\sigma_S/\sigma^*$) is smaller by $1/\beta^*$.

5.3 Some General Comments on Beam Beam Studies

There are some basic steps involved in these studies.

0) Get to the point where we can try it. We should be wary of beam beam experiments or studies before we've established "reasonable" colliding beam conditions. For beam beam experiments, almost everything has to be working. Also, for a valid test, we need realistic conditions. The pbars may be fine against proton intensities of 100.e9/bunch, but falling out against 300.e9/bunch. We don't expect to get many pbars during the Engineering Run (May to July 2000). Most of what we get will probably go to establishing 36 X 36 colliding beam conditions. So at the earliest, we would try this study during the Commissioning Run in Fall 2000.

1) Give it a try. Put in the crossing angle and see what happens. There are many beam beam experiments that are basically intended to "try out an idea". In my experience, for many of these : If it "works" or looks promising with more tuning, then great, its adopted. But if it doesn't work, its dropped, often without much effort at understanding **why** it didn't work. If we have problems with crossing angles, we may not have the luxury of dropping it.

1.5) If there are problems, are the conditions pretty much what we expect them to be ? Is something really wrong ? This is a big part of why we need to establish "reasonable" 36 X 36 (head on) colliding beam conditions before starting crossing angle studies. Are the linear optics OK ? Check for β waves, adjust the α^* bumps, check η^*. Check the separation between the beams at the IPs. Check the cogging. Is the separation in the arcs OK ? Do the separator bumps (both for separation at the IPs and for crossing angles at the IPs) do what's expected ? Are there problems with single beam resonances ?

Also as part of this, look at some "basic" measurements related to the crossing angles : the luminosity, tunes, and tune spectra as a function of crossing angle. Are these what we expect ?

2) If things are still bad even with the expected conditions, then we've got to try to **understand** what's happening. From simulations, what are the **mechanisms** by which particles get to large amplitudes? What are the important resonances and for what particle amplitudes are those resonances important ? What drives these resonances, the main IP, the first few near misses, the many crossings in the arcs ?

The conditions in the simulations will never be quite the same as what we have in the machine. We need to have a feel for why the simulations behave as they do if they are to give us some insight into what we need to change in the machine to improve performance.

5.4 End of Store Studies VS. Dedicated Stores

For End of Store Studies :

• Bigger emittances, smaller intensities

• Saves an hour or two of shot setup

• Has been easier to get machine time

• Slightly less prone to downtime. We get handed a working machine with beams in a "reasonable", stable condition.

• How much emphasis will there be on trying to recycle pbars ?

• We may at least start with the end of stores.

For Dedicated Stores :

• We have to do a full shot setup. If something breaks during shot setup, it still counts as time spent in our machine studies.

• We need dedicated stores to do 2 X 1 stores, 1 X 1 stores, or other "unusual" conditions. If we are doing unusual conditions, we may have trouble getting the beam to colliding beam conditions.

• Will have smaller emittances and higher intensities since we are getting the beams at the start of the store, rather than after they've been colliding for many hours. (Of course, we can always reduce the intensity or blow up the emittance if we desire.) The pbar intensity could be much higher if we only take a single bunch.

In either case :

How do we get to the crossing angle configuration ? Knob Separators ? Do we need to take out the lattice modifications for the collimation scheme ? Is the present collimation scheme OK for our proposed crossing angle configuration ? We should try the modifications to put in the crossing angle with a single beam first and make sure the mechanics work before we try it with colliding beams.

Also we want to make sure that any special instrumentation, diagnostics, or techniques for our studies are already checked out and working. If we're trying something special, we should try to establish the technique as much as possible with single beams in "easy conditions". As a simple example, we don't want to establish pbar tune measurements on crossing angle studies time.

The HEP experiments, CDF and D0, seem interested in 132 nsec bunch spacing. It looks like they will be encouraging us to make it work and put it into operation as soon as possible, provided of course there isn't too much loss of integrated luminosity. This will be a big help in getting machine time to do these studies.

The next year will be a very busy, exciting, interesting time at Fermilab. There is already a great deal of work to do and many unexpected problems are sure to crop up. Although it may not be easy, we feel that 36 bunch (396 nsec bunch spacing) operation can be made to work. This is sufficient for peak luminosities up to 1-2e32/(cm^2 sec).

Hopefully even before Run II officially starts in March 2001, we will begin some crossing angle studies to prepare for 132 nsec bunch spacing. These will be important to let us see what the problems are and to give us time to start to address them. At best, we expect 132 nsec operation with crossing angles to be difficult, and we may not be able to make it work at all.

REFERENCES

[1] Although it needs to be revised, the Run II Handbook is still a valuable reference. It is on the Web at http://www-bd.fnal.gov/lug/runII_handbook/RunII_index.html

[2] An up to date version of the Long Range Schedule for Fermilab should be available on the Web at http://www.fnal.gov/directorate/program_planning/PPO.html

[3] "Calculation of Integrated Luminosity for Beams Stored in the Tevatron Collider", D.A.Finley, FERMILAB-TM-1607, Mar 1989, 4pp. Also published in IEEE Part. Accel. 1989 :1834-6.